


## NuSTAR Gain Tracking

BRIAN W. GREFENSTETTE <sup>1</sup>, MURRAY BRIGHTMAN,<sup>1</sup> HANNAH P. EARNSHAW,<sup>1</sup> KARL FORSTER,<sup>1</sup>  
KRISTIN K. MADSEN,<sup>1,2</sup> AND HIROMASA MIYASAKA<sup>1</sup>

<sup>1</sup>*Space Radiation Lab  
California Institute of Technology  
1200 E California Blvd  
Pasadena, CA 91125, USA*

<sup>2</sup>*Goddard Space Flight Center, Greenbelt, MD 20771, USA*

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### ABSTRACT

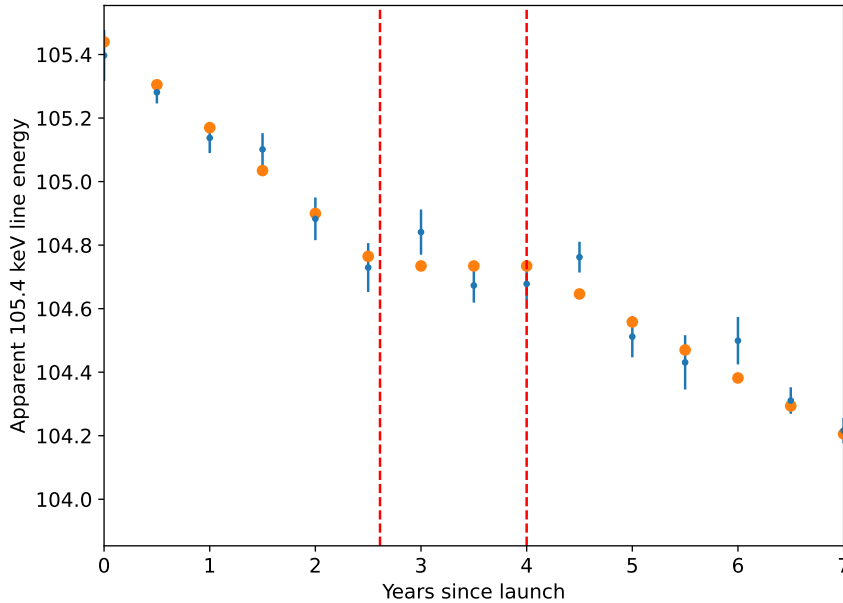
The memo describes the methods used to track the long-term gain variations in the *NuSTAR* detectors. It builds on the analysis presented in [Madsen et al. \(2015\)](#) using the deployable calibration source to measure the gain drift in the *NuSTAR* CdZnTe detectors. This is intended to be a “live” document that is periodically updated as new entries are required in the *NuSTAR* gain CALDB files. This document covers analysis up through mid-2021 and the gain v009 CALDB file released in version 20211020.

*Keywords:* Detectors

### 1. INTRODUCTION

The *Nuclear Spectroscopic Telescope ARray* (*NuSTAR*, [Harrison et al. 2013](#)) is a NASA Astrophysics Small Explorer observatory that launched in June of 2012. *NuSTAR* is composed of two co-aligned hard X-ray telescopes focused onto two focal plane arrays (hereafter FPMA and FPMB). We have previously described the time-dependent gain calibration of the detectors as a function of time ([Madsen et al. 2015](#)). Here we describe an updated approach to the time-dependent gain and our process for validating our time-dependent gain corrections to determine if any additional corrections as a function of time are required.

The conversion of the pulse heights (PHAs) collected by the *NuSTAR* detectors is a multi-stage process that relies on several underlying CALDB files (for a full description see the [NuSTAR data analysis software users guide](#)). Several corrections were made to the “charge-loss correction” (CLC) files after launch to account for differences in the gain for the FPMA detectors compared to pre-launch estimates using the in-flight <sup>155</sup>Eu calibration source. The primary gamma-ray decay lines are at high energy (86.54 and 105.4 keV), while there are several blended X-ray lines at low energy (including strong lines at 6.06 and 6.71 keV). In [Madsen et al. \(2015\)](#) we used two epochs of the calibration source just after launch in 2012 and in January 2015 to determine the time-dependent



**Figure 1.** Long-term trend of the apparent energy of the 105.4 keV line for FPMA DET0 with all time-dependence in the calibration files removed. The blue data points and error bars represent the line centroid for each epoch, while the orange circles are the best-fit piecewise linear function. The vertical dashed lines show the epochs of the 2015 gain calibration and the end of the plateau in 2016. Only data through the 2019 analysis is shown here.

change in the energy scale using the standard XSPEC formalism, where the transfer function to the correct  $PI$  values is:

$$PI' = PI/Slope - Offset \quad (1)$$

... where in Table 7 of [Madsen et al. \(2015\)](#) we allowed both the *Slope* and *Offset* values to vary as a function of time. Values were stored for the 2012 and 2015 epochs in the CALDB and the NuSTARDAS pipeline then interpolates the corrections to a given epoch for an observation.

In subsequent analyses of observations of the Crab, we noted that allowing the *Offset* parameter to vary with time was artificially introducing low energy residuals in the Crab spectrum. In practice, this implies that the charge-collection efficiency of the detectors may be slowly varying with time, while the overall offset of the PI-to-keV transfer function remains fixed.

We re-fit the 2012 and 2015 calibration source data with the *Offset* value frozen to zero, thereby forcing all time-dependent variations into the *Slope* parameter. This removed the artificial low-energy residuals in the Crab spectrum and was released in 2016. A full history of the *NuSTAR* gain calibration files is given in Appendix A.

The implementation of the gain CALDB files assumes that the variations are linear with time with the measured changes in the gain corresponding to a drop of 0.2% per year from 2012-2015 and remaining flat after January 2015.

Further long-term monitoring of the the gain is accomplished without risking the deployment of the source (which is mounted on a mechanical arm that moves in and out of the field of view). Here we report on the two methods used for monitoring the evolution of the *NuSTAR* gain: (1) monitoring the relative change in the *Slope* using high-energy background lines in the *NuSTAR* background and (2) monitoring any relative change in the *Offset* using the Kepler supernova remnant.

## 2. MONITORING LONG-TERM GAIN VARIATIONS

The *NuSTAR* internal background has several high-energy lines that we can use to determine the variation in the detector gain with time. However, as the *NuSTAR* background is also fairly low, this also requires a substantial amount of integration time to measure the central energy of the background lines.

We utilize all data where *NuSTAR* is pointed at the Earth (known as **OCCULTED** or “Mode 02” in NuSTARDAS parlance). While the *NuSTAR* optics formally cut off at 78.4 keV, the detectors are capable of extending to much higher energies. We use the data from 100 – 150 keV, which are relatively easy to interpret as the contributions mainly come from the internal background continuum component as well as lines from the calibration source at roughly 105, 122, and 144 keV.

### 2.1. 2019 Update

We reprocessed all of the data in the *NuSTAR* archive using the v004 CLC files and the v005 GAIN files (see Appendix A) so that we can remeasure the time dependence of the gain.

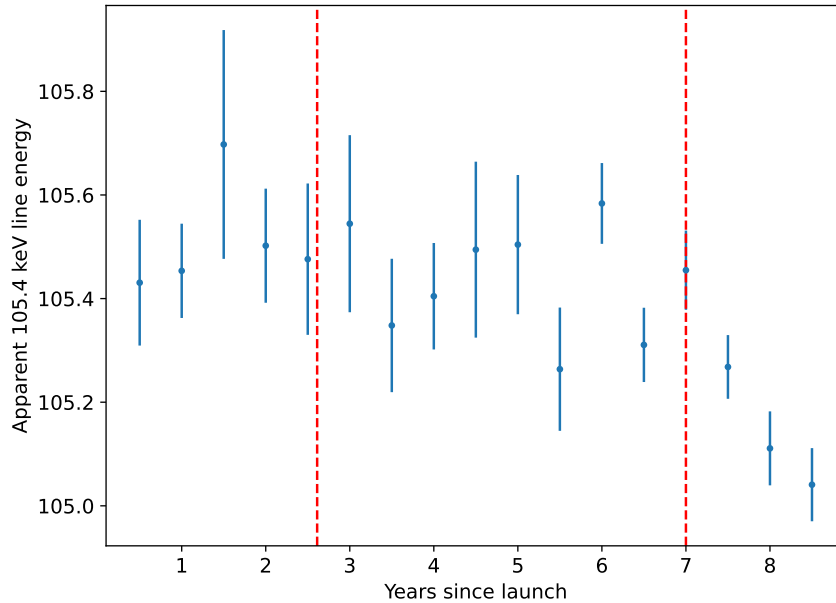
Data for each detector are integrated over six-month intervals, at which point we clean the data by requiring that the telescope bore-sight is more than  $3^\circ$  below the horizon to ensure that strong sources are fully blocked by the Earth. Standard **OCCULTED** data files include times when the bore-sight is  $3^\circ$  *above* the horizon, which is a conservative limit to avoid any attenuation in the Earth’s atmosphere. In addition, we require that the telescope is in Earth shadow to avoid any impact for solar activity.

For each epoch we then model the broad continuum using the standard broken power-law model (Wik et al. 2014) assumed to originate from down-scattered photons in the instrument. For this source we use a diagonal response matrix file (RMF) (rather than the *NuSTAR* CZT RMFs that are appropriate for photons normally-incident to the top surface of the detectors). Since the continuum model is dependent on the space weather conditions (which vary with time) we allow the power-law indices above and below the break energy (fixed to 124 keV for convenience) as well as the normalization of the broken power law to vary.

The line components are fit using several **gauss** components, some of which phenomenologically fit to the data (for  $E > 150$  keV) and some of which are known to originate from the radioactive  $^{155}\text{Eu}$  source. The ones primarily used for our analysis have line energies of 105.4 keV and 144.6 keV. There are also strong lines at lower energies, but these are contaminated by internal activation lines (which are also time-variable) in the CZT detectors and are not usable for this analysis.

After we obtain a good fit for each epoch we use the Goodman-Weare (Goodman & Weare 2010) MCMC implementation in XSPEC and **corner.py** (Foreman-Mackey 2016) to estimate the 90% quantiles and adopt these as the confidence limits for the 105.4 and 146.0 keV lines.

The trends for all eight detectors through mid-2019 are very similar. An example of the long-term gain trends is shown in Fig 1. The initial drop of 0.2% per year is confirmed as well as the flattening of the gain from 2015 to mid-2016. However, all eight detectors also show evidence of a further drop



**Figure 2.** Long-term trend of the apparent energy of the 105.4 keV line using the v008 CALDB gain file for FPMA DET0. The vertical dashed lines show the 2015 and 2019 CALDB entries. All 8 detectors showed similar trends.

in the measured line energy from 2017 to 2019. We model this as a piece-wise linear fit, allowing the date of the two pivot points and the slopes before and after each pivot point to vary. Between the pivots the gain is assumed to be flat. The results are given in Table 1. These changes in the gain were incorporated into the *NuSTAR* CALDB GAIN files as v008 in December, 2019.

The variations in the gain that we see are in family with the 0.2% per year decrease during the first three years of the mission. DET0 (where most point source targets are located) has shown a drop of only  $\sim 0.5\%$  and  $\sim 0.3\%$  since 2015 on FPMA and FPMB, respectively. At 6.4 keV, this represents a drop of  $\sim 30$  eV, or less than one *NuSTAR* energy channel, but which may be detectable in extremely bright sources with strong Fe lines. The 20191202 CALDB release corrects even this small drop.

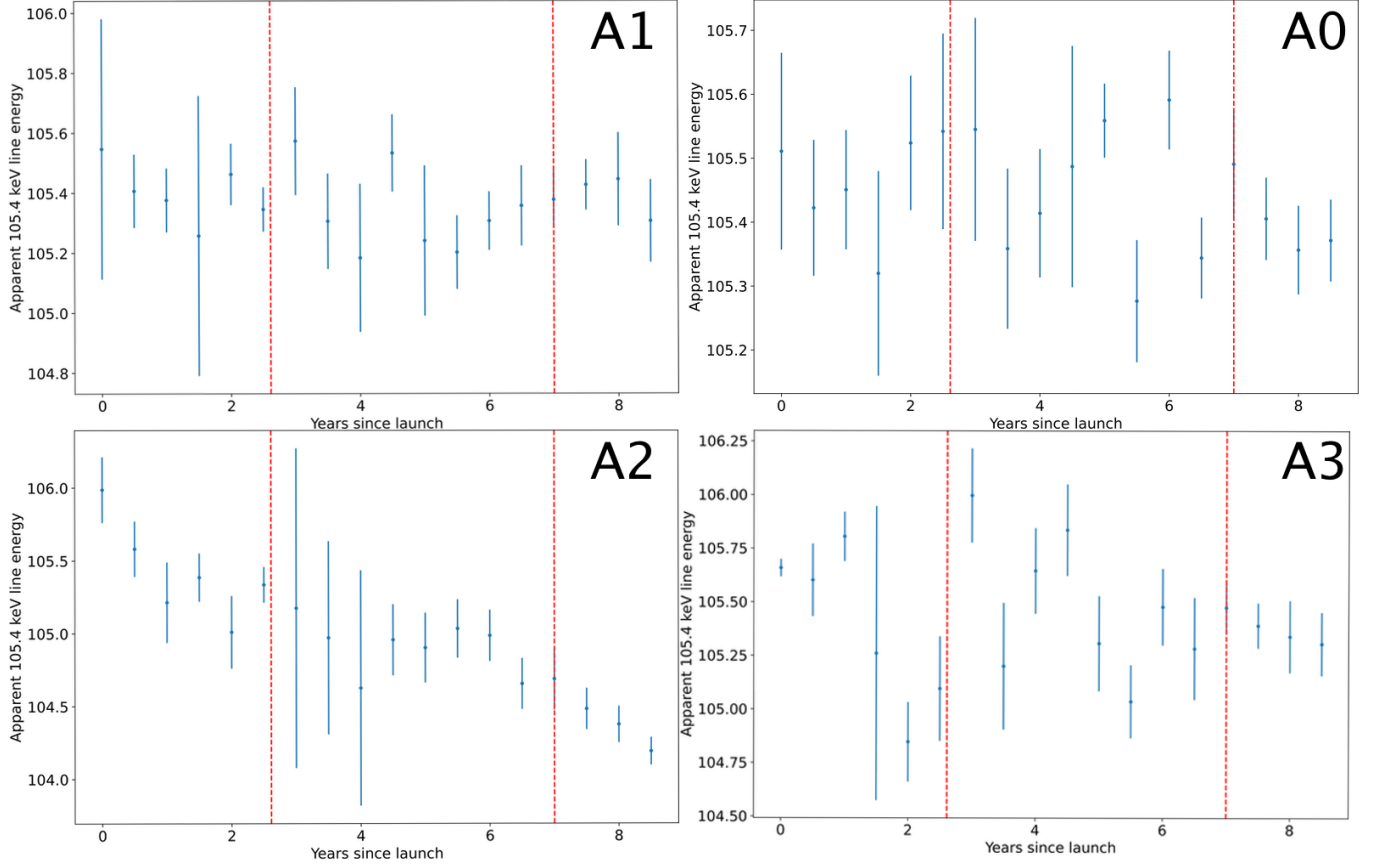
## 2.2. 2021 Update

We continued monitoring the apparent energy of the lines. By mid-2021 we noted a further drop in the line centroid location (Fig 2). All 8 detectors showed similar drops, so we applied a further gain correction in July of 2021 (Tab 1, Figures 3 and 4)

## 3. OFFSET MONITORING

In the above section, we have explicitly assumed that the gain change is only in the *Slope* parameter. We can also use astrophysical sources to monitor the low-energy response of *NuSTAR*. Unfortunately, there are few astrophysical sources with reliable, clean, narrow line emission in the *NuSTAR* band-pass. Instead, we use the Kepler supernova remnant (SNR).

The remnant itself is resolved and the Fe-emitting regions have a range of Doppler velocities, making an absolute measure of the line centroids impractical for *NuSTAR*. The Fe is not uniformly

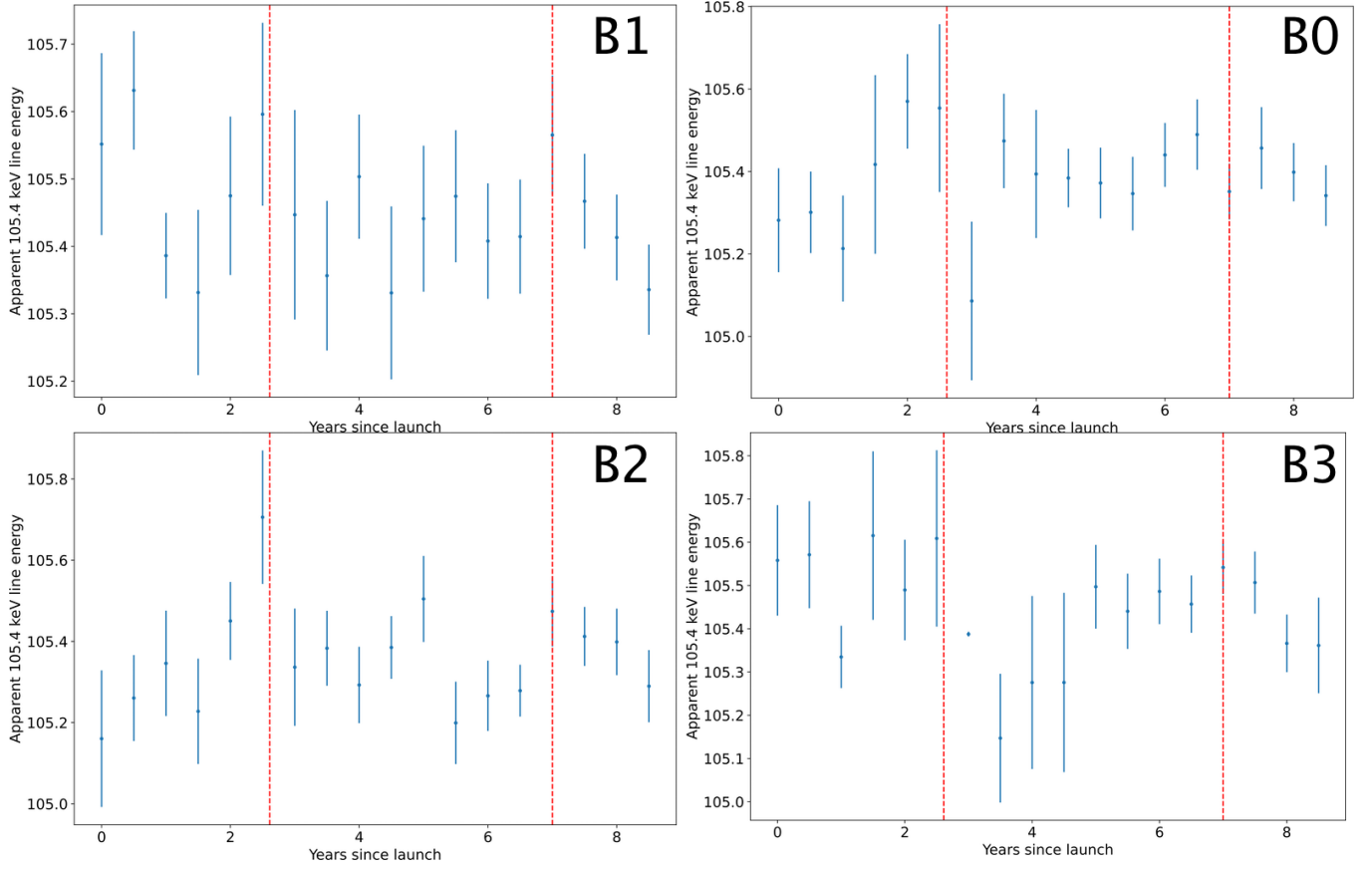


**Figure 3.** Apparent line centroids using CALDB v009 through July 2021 for the FPMA detectors.

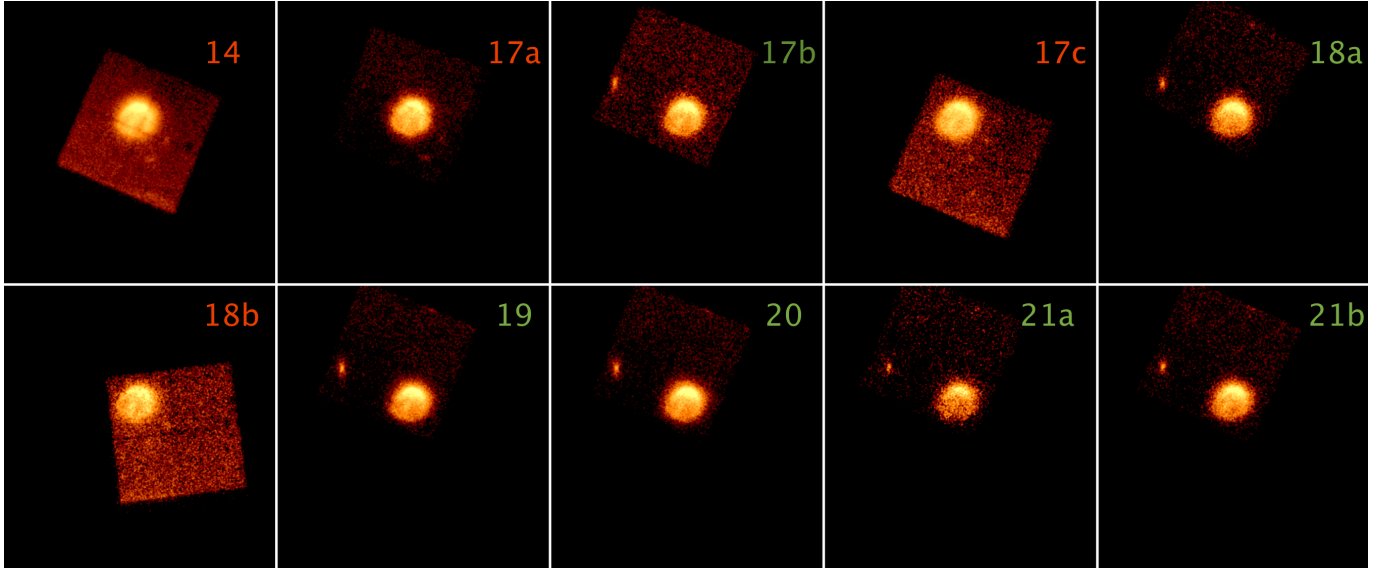
Module	Det0	Det1	Det2	Det3
Jan 2015 (v007)				
FPMA	0.9933	0.9919	0.9993	0.9973
FPMB	0.9955	0.9929	0.9928	0.9960
Jan 2015-Sep 2016 plateau (v008)				
FPMB	1.0*	1.0*	1.0*	1.0*
FPMA	1.0*	1.0*	1.0*	1.0*
June 2019 (v008)				
FPMA	0.995	0.994	0.995	0.993
FPMB	0.997	0.995	0.996	0.997
July 2021 (v009)				
FPMA	0.996	0.994	1.0*	0.994
FPMB	0.996	0.996	0.994	0.998

**Table 1.** The epochs, CALDB version numbers, and the applied changes over time at each epoch starting with the v007 CALDB file.

\*held fixed



**Figure 4.** Apparent line centroids using CALDB v009 through July 2021 for the FPMB detectors.



**Figure 5.** 3–20 keV images from FPMA of Kepler for the observations listed in Table 2. Observations used in the model fits are shown in green.

distributed, so any changes in the effective exposure (e.g., due to detector gaps) can result in a shift in the measured spectrum. However, by observing the remnant at the same orientation and in the same location on the focal plane we can perform a simple search for *relative* changes in the instrument response.

**Table 2.** Kepler Calibration Observations

Epoch	OBSID	Date	Exposure	PA	Used
14	40001020002	2014-10-11	246 ks	336°	No
17a	90201021002	2017-02-07	126 ks	158°	No
17b	90201021004	2017-04-22	51 ks	156°	Yes
17c	90201021006	2017-10-08	54 ks	336°	No
18a	90201021008	2018-06-04	42 ks	147°	Yes
18b	90201021010	2018-06-17	47 ks	6.2°	No
19	10501005002	2019-03-17	100 ks	158°	Yes
20	10601005002	2020-03-18	100 ks	157°	Yes
21a	10701407002	2021-05-04	18 ks	155°	No
21b	10701407004	2021-05-10	50 ks	155°	Yes

Table 2 gives the full list of observations. While all of these data are useful for scientific analyses, for calibration purposes we only select sequence IDs when the remnant is fully clear of any detector gaps. After 2018, the calibration observations were designed to have the same position angle (PA) to ensure that no artificial differences are present in the remnant. Figure 5 show the observations listed in Table 2, where we are only using the observations where the entire remnant is located on DET0 on both FPMs (with the epochs annotated in green).

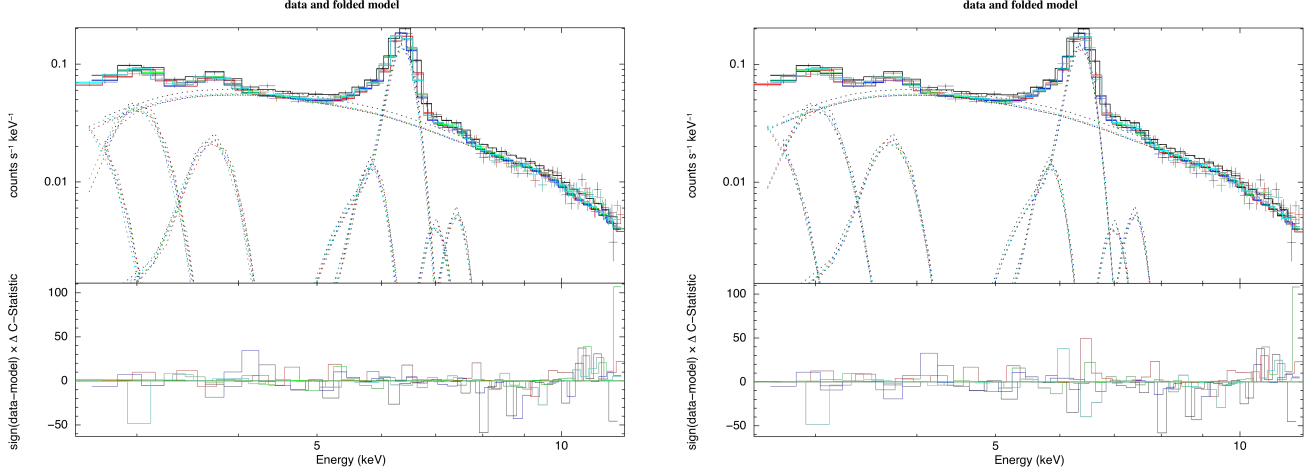
The remnant is compact (only 3-arcmin across), allowing us to easily integrate over the entire remnant. We concentrate on the low-energy X-ray band (2.5 – 10 keV) where the spectrum can be described by a phenomenological model consistent of an absorbed, hot ( $kT \sim 4$  keV) `nlaptec` along with seven `gauss` components. We note that the actual physics in the remnant is complex, so that the relative strength of the lines should not be physically interpreted from this simple model. We also note that over this energy range, the hot continuum component is essentially indistinguishable from a power-law. The atomic transitions are consistent with Si, S, Ar, Fe, and Ni. Except for the Fe-line complex, all of the lines are assumed to be narrow ( $\sigma$  fixed to 0.1 keV). In the Fe line region the line is slightly broadened due to Doppler broadening of the Fe-rich ejecta in the remnant.

### 3.1. Fitting procedure

We first reprocess all of the Kepler data using the v009 CALDB files described above. This should remove any variations in the energy scale associated with the long-term *Slope* drifts. All of the spectra are first rebinned using the FTGROUPPHA FTOOL and the optimally binning scheme from Kaastra & Bleeker (2016).

We simultaneously fit the five “good” epochs, ranging from 2017 through 2021 using the 2.7–12 keV energy band using our “standard” model. We arbitrarily pick Epoch 19 as a point reference since it has more exposure than Epoch 17b. We used the “gain fit” formalism in XSPEC, freeze





**Figure 6.** Spectrum of the Kepler SNR used to fit the gain. Each epoch is between 50-ks and 100-ks of exposure and has been “optimally” binned (see text). The black, red, green, blue, and cyan data are for FPMB during epoch 17b, 18a, 19, 20, and 21b, respectively. The left panel shows the data after the gain fit has been applied, while the right figure shows after the gain fit has been applied.

the *Slope* parameter, and allow the *Offset* to values to vary for each epoch and fit for the continuum parameters, the line fluxes and line centroids, and (for the Fe complex) the line width (Figure 6).

Table 3 gives the **rerror** with a 2.706 delta-chi error range for the *Offset* values for each of the epochs and for each FPM. All of the epochs have a fit value less than one *NuSTAR* channel (0.04 eV) and are consistent with the *Offset* value being consistent with 0.0 except for Epoch 21b. While the fits are statistically improved when applying the gain fit (*cstat* 217/193 d.o.f. after the gain fit vs 250/195 before), it’s not clear how such a small shift in the response edges is producing this significant change in the fit statistic.

All the same, we do note a slight trend in the energy with time at the 20 eV level. The scatter in the *Slope* measurements above are on the order of 0.1 keV at 105.4 keV. Applying such a residual gain error at 6 keV results in an expected scatter on the order of 10s of eV. So it’s possible that the residual trends are the result of un-modeled temporal changes in the *Slope* parameter. Overall, we do not have significant evidence that the low-energy energy scale is changing with time on scales larger than the quoted systematic error of  $\approx 40$  eV (one *NuSTAR* channel).

We will continue monitoring the Kepler SNR in the future to see if this trend continues in 2022 and could result in an update of the *Offset* parameter as well as the *Slope* value.

## APPENDIX

### A. HISTORY OF *NuSTAR* GAIN-RELATED CALDB FILES:

Below are the documentation of the various *NuSTAR* CALDB files released since launch. There are two relevant files, the “pixel gain” (GAIN) file and the “charge loss correction” (CLC) file. At various times one or both of these have been updated, so it’s useful to keep track of these files here and for reference in this paper.

- `nu[A/B]clc20100101v001.fits` | `nu[A/B]gain20100101v004.fits`



**Table 3.** Kepler fit parameters

Epoch	FPMA Offset (keV)	FPMB Offset (keV)
17b	$0.02 \pm 0.01$	$0. \pm 0.1$
18a	$0.02 \pm 0.01$	$0.01 \pm 0.01$
19	$0^*$	$0.0^*$
20	$-0.02 \pm 0.01$	$-0.01 \pm 0.1$
21b	$-0.02 \pm 0.01$	$-0.03 \pm 0.01$

Pre-launch values based on ground calibration data and data obtained during environmental testing (for FPMB).

- nu[A/B]clc20100101v002.fits | nu[A/B]gain20100101v005.fits

Released in July 2012 with updated based on 2012 in-flight calibration source data. No time dependence on *Slope* or *Offset*. Contains large corrections to FPMA, smaller corrections to FPMB.

- nu[A/B]clc20100101v003.fits | nu[A/B]gain20100101v005.fits

Released in April 2014 and contain updated pixel-by-pixel *Slope* and *Offset* corrections to improve performance. Generally small corrections for most detectors, though large changes for FPMA DET2, which was not updated in the v002 data.

- nu[A/B]clc20100101v004.fits | nu[A/B]gain20100101v006.fits

Released in March 2015 and the first data set based on the 2015  $^{155}\text{Eu}$  source deployment. The CLC file was update based on revised analysis of 2012 data and time-dependent *Slope* and *Offset* values were stored in the gain file.

- nu[A/B]clc20100101v004.fits | nu[A/B]gain20100101v007.fits

Released in July 2016. Reverts to using the 005 version of the gain file with the 004 version of the CLC and performs a cross-correlation between the 2012 and 2015 calibration data sets to determine the change in the *Slope* parameter. The *Offset* parameter is not allowed to vary with time.

- nu[A/B]clc20100101v004.fits | nu[A/B]gain20100101v008.fits

Released in December 2019 and based on the methods described in this paper.

## B. INTERNAL LIST OF GAIN FILES

List includes CALDB files since the 2015 release, and only the gain files.

- vcit011

Did not track the intermediate plateau between 2015 and 2019 (unreleased)

- vcit012

First fix of the bug (unreleased)

- vcit013  
Allowed FPMA DET3 to have a single linear slope across the time range (unreleased).
- vcit014  
Fits for FPMA DET2 gain drift in epoch 1 (unreleased)
- vcit015  
FPMA DET2 gain offset at launch (→ released as version 008)
- vcit016  
2021 gain updates (→ released as version 009)

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